Observation of hot electrons in molybdenum

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The dependences of the electron temperature T_e of lenses and of the hole temperature T_h of ellipsoids on the power supplied to the sample as a result of transmission of a current through microcontacts have been measured from quantum-oscillation amplitudes of the surface impedance of molybdenum. It was found that $T_h \approx T_e$ under the contact, that $\Delta T_h \approx 2\Delta T_e$ at some distance from it and that it exceeds the temperature increase of phonons $\Delta T \lesssim \Delta T_e$.

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Krylov and Sharvin[1] showed that a hot-electron channel is formed in a quantizing magnetic field of bismuth when a current is transmitted through microcontacts. The observed effect is apparently linked with the small dimensions of the Fermi surface of bismuth and hence with the long energy relaxation time.[2] On the other hand, there are reasons to assume[3,4] that the frequency of electron-electron collisions ν_{ee} in molybdenum is large at low temperatures compared with the electron-phonon collision frequency ν_{ep}; the condition for thermalization of electron gas ($\nu_{ee} \gg \nu_{ep}$) is therefore satisfied, thus making it possible to produce hot electrons in this metal.[5]

The experimental setup is similar to that in Ref. 1, except for the separate thermometer (see the inset in Fig. 2). A molybdenum sample in the form of a 1 X 2 X 20-mm single-crystal parallelepiped with an electrical-resistance ratio $R_{300\ \mathrm{K}}/R_{4.2\ \mathrm{K}} \approx 5 \times 10^4$ was placed in a cryostat with superfluid helium. Clamped molybdenum microcontacts were attached to the sides of the sample. One of the microcontacts (the nearer) was inserted inside a flat, 1-mm-diam coil that was glued to the sample. The other microcontact (the farther) was attached to the opposite side of the sample, so that the contact line was parallel to the ⟨100⟩ axis and to the direction of the magnetic field **H**.

The spiral coil, which was used as the inductance of the rf circuit of the autodyne generator, made it possible to measure, using a modulation technique,[6] the quantum oscillations of the derivative of the active part of the surface impedance of the sample, $\partial R/\partial H$. According to the Lifshitz-Kosevich formula, the oscillation amplitude A is determined by the temperature T of the electron gas

$$A \sim T \exp\left[-\frac{2\pi^2 k_B}{\hbar\Omega}(T + T_D)\right]. \tag{1}$$

Here k_B is the Boltzmann constant, T_D is the Dingle temperature, and $\Omega = eH/mc$ is the cyclotron frequency of electrons with a mass m. This made it possible to determine the dependence of the temperatures of the different groups of electrons on the current transmitted through the microcontact from the amplitudes of the corres-

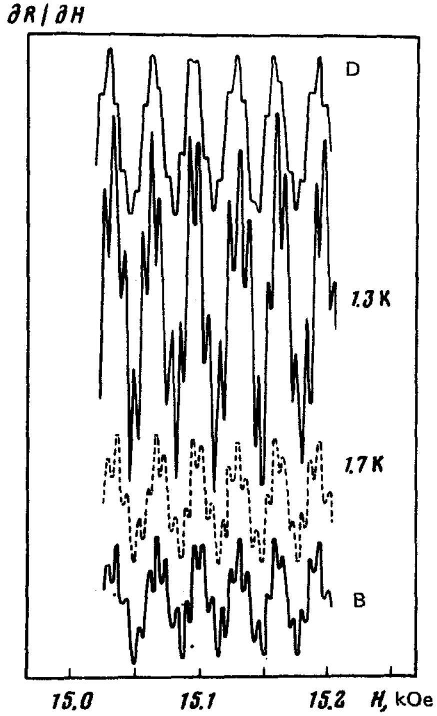

FIG. 1. Trace of the quantum oscillations of the surface impedance of molybdenum for different temperatures of the sample when the current is transmitted through the near contact ($I = 50$ mA, $R = 6.3\ \Omega$) and through the far contact ($I = 13$ mA, $R = 24.5\ \Omega$).

ponding oscillation periods. The experiments were conducted at at frequency of 8-MHz and at a depth of the skin layer $\delta \approx 0.05$ mm.[7] As a result, we were able to measure the temperature of the different groups of electrons in the central cross sections of the Fermi surface in the surface layer of the sample of depth δ and 1-mm diameter.

As seen in Fig. 1, there are two oscillation periods—rf oscillations with a frequency $F = 24$ MHz, which correspond to the central cross sections of the hole ellipsoids, and low-frequency oscillations ($F = 5.4$ MHz), which are attributable to the electron lenses. Since the cyclotron masses at these cross sections are quite close (0.38 m_0 and 0.34 m_0 for holes and electrons, respectively[8]), the $A(T)$ dependences for these periods, which were calibrated according to the temperature variation of the sample were almost identical in the temperature range 1.3 K–2.5 K (see Fig. 1).

The oscillation amplitudes decreased sharply as a result of transmission of a weak current I through one of the contacts and through either end of the sample at 1.3 K (Fig. 1). Note the following experimental peculiarities. 1) The maximum reduction of the amplitude, which occurs when the current is transmitted through the far contact, vanishes abruptly when the contact line shifts by an angle $\phi > 10^\circ$ from the **H** axis. 2) This effect decreased by an order of magnitude when a square coil containing the sample was substituted for the spiral coil. 3) The contact resistance R, which varied from 1 Ω to 30 Ω from one experiment to another, consistent with the variation of the contact diameter from 250 Å to 50 Å,[9] did not affect the dependence of A on the power P. 4) This is a square-law effect with respect to the current:

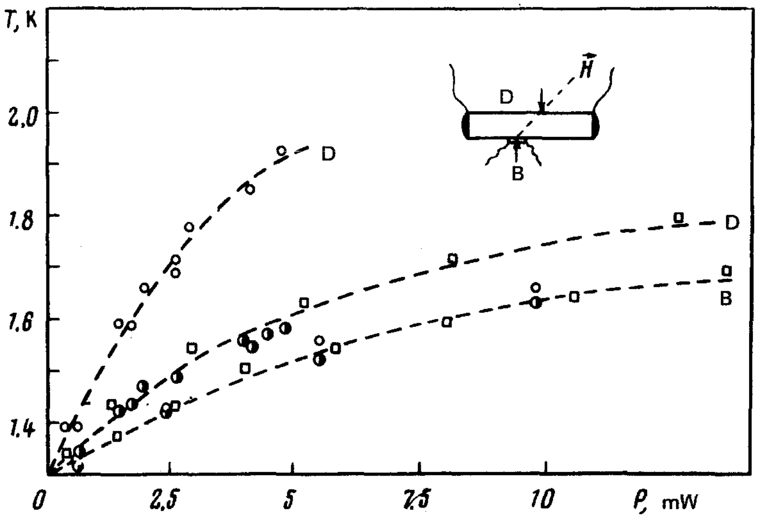

FIG. 2. Dependence of the electron temperature of the lenses (◑) and of the hole temperature of the ellipsoids (○) on the power supplied through the far and the near microcontacts. The symbol □ denotes the data obtained for electrons of the lenses as a result of suppression of the hole oscillations by the modulating field (R_B = 1.6 Ω, R_D = 4.5 Ω). The points correspond to the data obtained in different experiments and for different values of R.

a transmission of an ac current with a frequency f_m = 10 Hz–1 kHz (at zero modulation field) through a microcontact produced quantum oscillations when a synchronous amplifier was tuned to the doubled frequency $2f_m$, whose amplitude was two orders of magnitude larger than that at the frequency f_m. The oscillations at $2f_m$ started at 2.5 K, increased sharply in amplitude with decreasing temperature, but decreased abruptly severalfold after passing through the λ point at helium.

Thus the oscillation amplitude apparently decreases because of the local heating of electron gas. We can see from Fig. 2 that 1) the hole temperature increases twice as much as the electron temperature and therefore as the phonon temperature also, when the heating is accomplished through the "far" contact and 2) the electron temperature is the same as the hole temperature when the heating is accomplished through the "near" contact, i.e., under the contact.

The microcontact apparently serves as a point-contact heater of the sample because of the generation of nonequilibrium phonons under the contact.[9] This gives rise to the formation of a hot-electron channel whose divergence with respect to the thermometer size leads to a difference in T when the heating is accomplished through the far and the near contacts. Isotropization of the distribution function of electrons, heated under the contact, along the Fermi surface as a result of motion along the magnetic field occurs because of electron-electron scattering as well as electron-impurity scattering. The difference between T_e and T_h at some distance from the contact is due to the different velocities of this isotropization, but the specific reason for this difference as well as the role of these scattering mechanisms remain unclear. Further studies of the $T(P)$ dependence for the "jack" and the octahedron, as well as for the other metals, with a weak electron-electron scattering will probably help answer these questions.

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1. I. P. Krylov and Yu. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 166 (1976) [JETP Lett. **23**, 146 (1976)].
2. V. T. Dolgopolov, Usp. Fiz. Nauk **130**, 241 (1980) [Sov. Phys. Uspekhi **23**, 134 (1980)].
3. M. A. Arutyunyan and V. A. Gasparov, Zh. Eksp. Teor. Fiz. **76**, 369 (1979) [Sov. Phys.–JETP **49**, 188 (1979)].
4. V. A. Gasparov, I. F. Voloshin, and L. M. Fisher, Sol. St. Comm. **29**, 43 (1979).
5. M. I. Kaganov, I. M. Lifshitz, and L. V. Tanatarov, Zh. Eksp. Teor. Fiz. **33**, 1261 (1957) [Sov. Phys.–JETP **6**, 970 (1957)].
6. E. P. Vol'skiĭ, Zh. Eksp. Teor. Fiz. **43**, 1120 (1962); **46**, 123 (1964) [Sov. Phys.–JETP **16**, 791 (1962); **19**, 89 (1964)].
7. I. F. Voloshin, V. G. Skobov, L. M. Fisher, and A. S. Chernov, Zh. Eksp. Teor. Fiz. **78**, 339 (1980) [Sov. Phys.–JETP **51**, 170 (1980)].
8. K. Dobson and A. Myers, Sol. St. Comm. **35**, 27 (1980).
9. Yu. V. Sharvin and N. I. Bogatina, Zh. Eksp. Teor. Fiz. **56**, 772 (1969) [Sov. Phys.–JETP **29**, 419 (1969)].

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